Mitigation of EEPN in Long-Haul *n*-PSK Coherent Transmission System Using Modified Optical Pilot Carrier

Tianhua Xu[1,2], Gunnar Jacobsen[2], Sergei Popov[1], Jie Li[2], Sergey Sergeyev[3]
1. School of ICT, Royal Institute of Technology, Stockholm, SE-16440, Sweden,
2. Acreo Swedish ICT AB, Electrum 236, SE-16440, Kista, Sweden,
3. Aston University, Birmingham, B47ET, UK
Author e-mail address: tianhua@kth.se

Abstract: We present the compensation of the equalization enhanced phase noise (EEPN) in the long-haul *n*-level phase shift keying (*n*-PSK) coherent optical transmission system, by employing a scheme of phase modulated optical pilot carrier.
OCIS codes: (060.1660) Coherent communications; (060.2330) Fiber optics communications

1. Introduction

Coherent detection has become one of the most promising technologies for next generation high speed transmission networks due to the high power and spectral efficiencies. Using advanced digital signal processing (DSP) techniques, coherent optical receivers can compensate the system impairments, such as chromatic dispersion (CD), polarization mode dispersion (PMD), laser phase noise (PN) and fiber nonlinearities in the electrical domain [1-3]. Several DSP algorithms have been validated as effective methods for CD equalization (CDE) and carrier phase estimation (CPE) [1-3]. There is a complicated interplay between the electronic CDE and the laser PN, which leads to an effect of equalization enhanced phase noise (EEPN) [4-6]. The EEPN will significantly degrade the performance of coherent communication systems with the increment of the fiber length and the symbol rate [4,5]. Some studies have been performed to compensate the EEPN by employing DSP, such as using a Viterbi-Viterbi (VV) algorithm [7]. Our previous work has also investigated the mitigation of the EEPN by using a traditional normal optical pilot carrier (TN-OPC), but the effect of improvement is marginal [8].

In this paper, we investigate the mitigation of EEPN in the long-haul *n*-level phase shift keying (*n*-PSK) coherent optical communication system by using a modified optical pilot carrier (M-OPC). In the M-OPC scheme, we introduce a modulation of the OPC phase, which is correlated with the phase modulation of the *n*-PSK signal. The simulation work is carried out in a 28-Gsymbol/s quadrature phase shift keying (QPSK) coherent transmission system with a transmission distance of 3000 km. The results are compared to using the VV algorithm for the compensation of EEPN.

2. Principle of equalization enhanced phase noise

The coherent communication system using electronic CDE and CPE is depicted in Fig. 1. The transmitter (Tx) laser PN passes through both the transmission fiber and the electronic CDE module, and so the net dispersion experienced by the transmitter PN is close to zero. However, the local oscillator (LO) phase noise only goes through the electronic CDE module, which is heavily dispersed in a transmission system without any dispersion compensation fibers (DCFs). Therefore, the LO phase noise will interact with the electronic CDE, resulting in the effect of EEPN. It has been demonstrated that the EEPN scales linearly with the accumulated CD and the linewidth of LO laser [4,5].

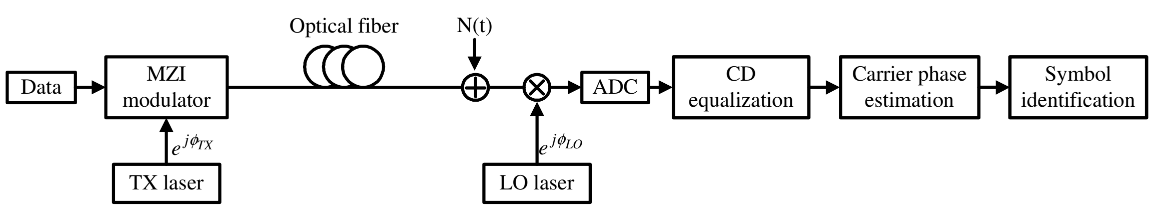

Fig. 1. Block diagram of EEPN in coherent transmission system with electronic CD equalization

3. High speed coherent optical transmission system using the modified OPC

The 28-Gsymbol/s QPSK coherent optical transmission system is implemented based on the VPI platform, as shown in Fig. 2. We consider the system with two cases in the Tx: (a) the use of TN-OPC, (b) the use of M-OPC. In the TN-OPC scheme, one polarization is used for the normal QPSK signal, and the other is used for the traditional OPC [8]. In the M-OPC scheme, the modified OPC includes part of the modulated signal. One polarization has a total four level phase modulation amplitude of 2πα (0≤α≤1), and the other has a phase modulation amplitude of 2π(α-1). Here we choose α=0.5 to generate the best EEPN correlation between the two polarizations [9]. The complex conjugate multiplication in the receiver (Rx) will remove the intrinsic PN from the Tx and LO lasers, as well as the EEPN contribution in the best possible way. Then the normal QPSK modulated deterministic signal will be recovered. We note that the case of α=1 in the M-OPC scheme is equal to the case of TN-OPC.

The CD coefficient of transmission fiber is 16 ps/nm/km, and the central wavelengths of the Tx and the LO lasers are both 1553.6 nm. The CD compensation is performed by using a frequency domain equalizer (FDE) [2]. For simplicity, the influences of fiber attenuation, PMD and nonlinear effects are neglected.

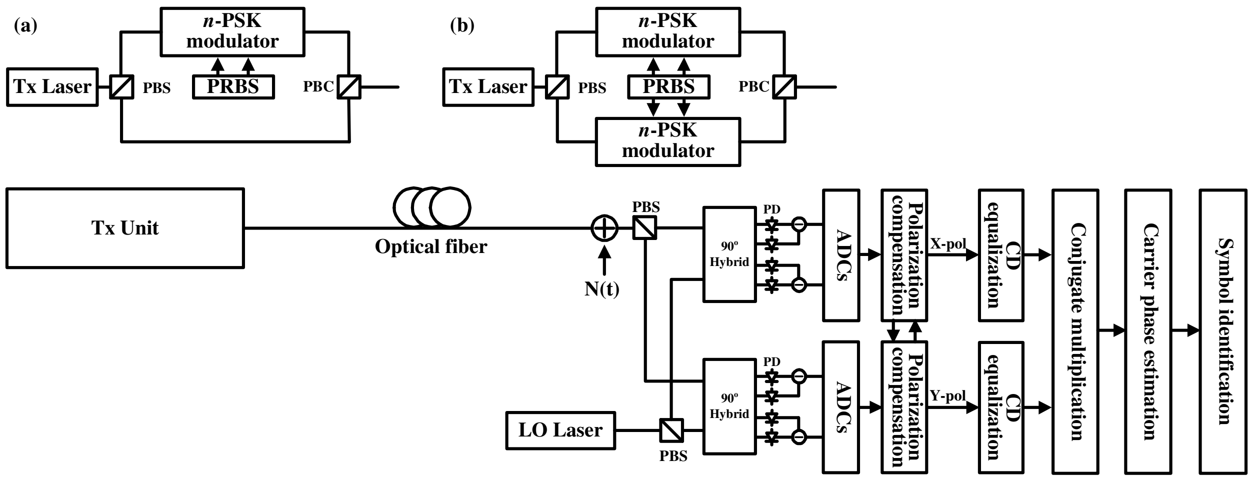

Fig. 2. Diagram of QPSK coherent optical transmission system, (a) TN-OPC scheme, (b) M-OPC scheme.

4. Simulation results and discussion

In our numerical simulation, we consider a long-haul coherent transmission system with a fiber length of 3000 km, and the linewidths of the Tx and the LO lasers are both 5 MHz. In Fig. 3, the constellations of the recovered signals within the schemes of using TN-OPC and M-OPC are studied respectively. Simulation results are compared to further using the VV algorithm. The optical signal-to-noise ratio (OSNR) in Fig. 3 is 40 dB, where EEPN is absolutely dominant to generate the bit-error-rate (BER) floor. We find in Fig. 3(a) that, the signal constellation is influenced partly by phase noise (banana-shape) and partly by amplitude noise (circular). In Fig. 3(b), the use of VV algorithm can remove the influence of the phase noise significantly. Fig. 3(c) and Fig. 3(d) show the constellations of the recovered signals within the use of the M-OPC. It appears that this scheme generates EEPN which is partly correlated with the QPSK symbols. We can find that the two upper symbols are dominated by PN, while the lower symbols are dominated by amplitude noise. Meanwhile, the VV algorithm does not improve the signal in this case, where the noise in the constellation is modulation dependent.

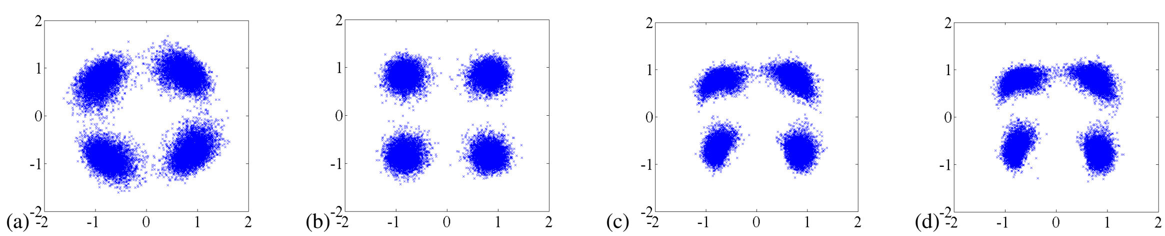

Fig. 3. Constellations of the recovered signals at OSNR=40dB.
(a) TN-OPC, without VV, (b) TN-OPC, with VV, (c) M-OPC, without VV, (d) M-OPC, with VV.

In Fig. 4, we show the BER performance of EEPN mitigation in the coherent transmission system using the TN-OPC and the M-OPC respectively, and the results are compared to further using the VV algorithm. We find that the EEPN is not compensated by the TN-OPC (only intrinsic PN from Tx and Rx lasers can be cancelled), and the resulting BER-floor is 3×10^{-3}. While in the use of M-OPC, part of the EEPN is cancelled, resulting in a BER-floor of 7×10^{-4}. The implementation of the balanced phase modulation in two polarizations creates a partly correlated EEPN, and the EEPN cancellation improves the BER floor by around 1/2 order of magnitude. Then we investigate the use of the VV algorithm. We find that the improvement is very considerable for the QPSK coherent system with the TN-OPC. An improvement of the BER floor of around 3/2 orders of magnitude can be achieved. But the use of the VV algorithm does not improve the situation for the M-OPC case. We also note that the simulation results in the use of TN-OPC (with or without using VV algorithm) are consistent with the results in previous report [7], which is used as the reference (red triangle mark) in Fig. 4.

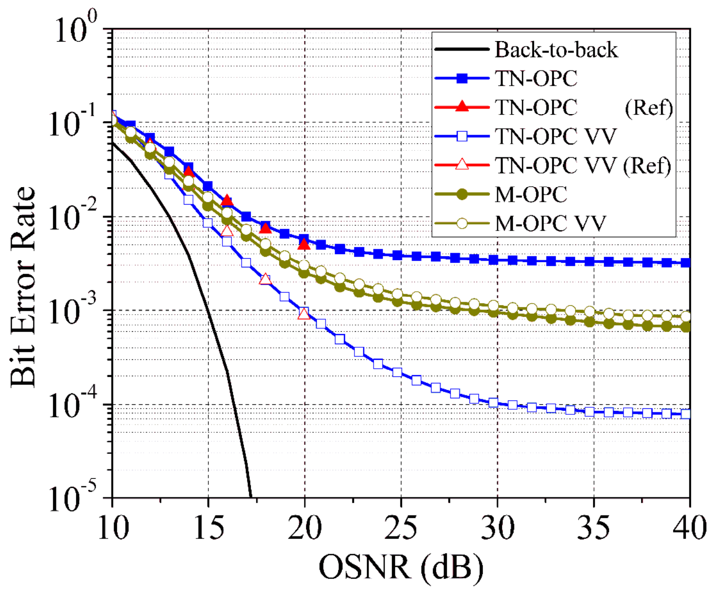

Fig. 4. Performance of EEPN mitigation using T-OPC and M-OPC. Results are compared to using VV algorithm.

5. Conclusions

In this paper, we propose a scheme of modified optical pilot carrier (M-OPC) to mitigate the EEPN in the *n*-PSK coherent transmission system, by introducing a balanced phase modulation between two orthogonal polarizations of the transmitter. An improvement of about 1/2 order of magnitude in BER floor position is obtained. Results are compared to using the Viterbi-Viterbi (VV) algorithm to mitigate the EEPN in a classical QPSK system. The VV method improves the BER floor by around 3/2 orders of magnitude. However, the VV algorithm can not improve the EEPN sensitivity any further for the system within the M-OPC scheme. Important novel insight into the statistical properties of EEPN has been discussed, and some interesting subjects need to be further investigated.

6. References

[1] S. J. Savory, "Digital filters for coherent optical receivers," OE **16**, 804-817 (2008).

[2] T. Xu, G. Jacobsen, S. Popov, J. Li, E. Vanin, K. Wang, A. T. Friberg and Y. Zhang, "Chromatic dispersion compensation in coherent transmission system using digital filters," OE **18**, 16243-16257 (2010).

[3] A. Viterbi, "Nonlinear estimation of PSK-modulated carrier phase with application to burst digital transmission," TIT **29**, 543-551 (1983).

[4] W. Shieh and K. P. Ho, "Equalization-enhanced phase noise for coherent detection systems using electronic digital signal processing," OE **16**, 15718-15727 (2008).

[5] A. P. T. Lau, T. S. R. Shen, W. Shieh and K. P. Ho, "Equalization-enhanced phase noise for 100Gb/s transmission and beyond with coherent detection," OE **18**, 17239-17251 (2010).

[6] C. Xie, "Local oscillator phase noise induced penalties in optical coherent detection systems using electronic chromatic dispersion compensation," in OFC 2009 (San Diego, California, 2009), paper OMT4.

[7] R. Farhoudi, A. Ghazisaeidi and L. A. Rusch, "Performance of carrier phase recovery for electronically dispersion compensated coherent systems," OE **19**, 26568-26582 (2012).

[8] G. Jacobsen, T. Xu, S. Popov, J. Li, A.T. Friberg and Y. Zhang, "Receiver implemented RF pilot tone phase noise mitigation in coherent optical nPSK and nQAM systems," OE **19**, 14487-14494 (2011).

[9] G. Jacobsen, T. Xu, S. Popov and S. Sergeyev, "Study of EEPN mitigation using modified RF pilot and Viterbi-Viterbi based phase noise compensation," OE **21**, 12351-12362 (2013).